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Abstract

A distributed daily rainfall–runoff model is applied to the Tejo and Guadiana river basins in Spain and Portugal to simulate the effects of climate change on runoff production, river flows and water resource availability with results aggregated to the monthly level. The model is calibrated, validated and then used for a series of climate change impact assessments for the period 2070–2100. Future scenarios are derived from the HadRM3H regional climate model (RCM) using two techniques: firstly a bias-corrected RCM output, with monthly mean correction factors calculated from observed rainfall records; and, secondly, a circulation-pattern-based stochastic rainfall model. Major reductions in rainfall and streamflow are projected throughout the year; these results differ from those for previous studies where winter increases are projected. Despite uncertainties in the representation of heavily managed river systems, the projected impacts are serious and pose major threats to the maintenance of bipartite water treaties between Spain and Portugal and the supply of water to urban and rural regions of Portugal.

Keywords: climate change impacts, international river basin, rainfall-runoff model, climate ensemble scenarios

Introduction

Water resources in Iberia are of considerable concern and controversy due to the historic water stress and the generally recognised assertion that the region is experiencing decreases in precipitation and streamflow (Houghton *et al.,* 2001). Portugal and Spain experience considerable variability in inter-annual rainfall (Serrano *et al*., 1999) and a drought in 2004–2005 was the most severe since the 1940s; rainfall in some regions was the lowest in the 105-year record (INAG, 2005). The drought required the imposition of major water restrictions and resulted in serious reductions in agricultural production, while more than 300 000 ha of land were affected by forest fires. Portugal demanded €6m in compensation from Spain after flows in the Douro river fell below limits established by a bilateral agreement.

According to Corte-Real *et al.* (1999), a negative trend has already been detected in March precipitation in southern Portugal. Trigo *et al.* (2004) review the current climate and water stress in the region and analyse the strong linkage of rainfall and river flow to the North Atlantic Oscillation Index (NAO), showing that the magnitude of the NAO influence is large for Iberian rivers. The upward trend in the NAO, from the 1960s to the early 1990s, has coincided with the winter warming of Northern Hemisphere land masses.

Climate models forced with SRES A2 and B2 scenarios indicate little change in precipitation over the Mediterranean in winter (DJF, –5 to 5%). However, in summer (JJA), a large decrease in precipitation (< –20%) is predicted under A2 (Houghton *et al.*, 2001). River discharges of zero which currently occur in summer may in future persist for several months. By 2050, low flows in Portugal and Spain are expected to decrease.

In Portugal the water balance is particularly fragile due to the semi-arid climate; dependence on international resources and the dominance of agriculture in water use account for 79% of national demand (EEA, 1996). The irregularity and intensity of rainfall, high inter-annual variability in rainfall and temperature and over-exploited systems are all influencing factors. Large surface water storage reservoirs are increasingly relied upon to meet water demands under increasing water scarcity. Groundwater resources also play a significant role, although there has been little research into climate impacts in the Mediterranean region and integrated catchment management has yet to be widely adopted in southern Europe.

This work assesses the impacts of climate change on the water resources of the Tejo and Guadiana rivers in the context of international agreements.

The specific objectives are to:

1. establish a hydrological model capable of simulating the monthly natural flows in the Tejo and Guadiana basins and validate using observations;
2. generate ensembles of future rainfall and evaporation series using two downscaling methods, for a range of representative scenarios to use as inputs to the hydrological model;
3. compare the scenarios generated by these two different methods;
4. simulate projected future conditions using the hydrological model and assess changes from the current situation.

The study area

HYDRO-CLIMATE AND WATER MANAGEMENT OF THE TEJO AND GUADIANA BASINS

A comprehensive review of the shared waters of the Iberian Peninsula, annual mean water resources and uses (Maia, 2000; EEA, 1996, 2003) provides statistics of freshwater resources and abstractions in Portugal and Spain. The World Map of Arid Zones (EEA, 1996) classifies southern Portugal in the semi-arid zone category (P/PET <0.5, where P is precipitation and PET is potential evapotranspiration, Table 1).

The climate has two well defined annual periods — wet (October to April) and dry (May to September) — so the soil is unsaturated for most of the year with low aquifer recharge. Rainfall is strongly heterogeneous spatially and small intense storms are common. Mean annual PET in Portuguese semi-arid areas is some 1500 mm yr^{-1}; rates in central arid Spain are somewhat lower.

The Douro, Tejo (*Tajo* in Spanish, also known as *Tagus*) and Guadiana are the principal river basins shared between Spain and Portugal. The storage capacity favours Spain, while Spain's intensive utilisation of some 70% of the annual mean water resources has led to a progressive decrease in the mean flows and an increased irregularity of the flow regime (Maia, 2000). Surface-groundwater interactions can

Table 1. Moisture index (P/PET) for the Guadiana and Tejo catchments (From EEA, 1996)

	P (*mm/year*)	*PET* (*mm/year*)	*P/PET*
PORTUGAL			
Tejo (24 860[a] km^{2})	687	1381	0.50
Guadiana (11 700 km^2)	564	1304	0.43
Total (all regions)	649	1399	0.46
ET = 478 mm/year			
SPAIN			
Guadiana (60 000 km^2)	557523	933	0.60
Total (all regions)	557523	917	0.57
ET = 444 mm/year			

[a] = Total surface area of Portuguese Tejo basin

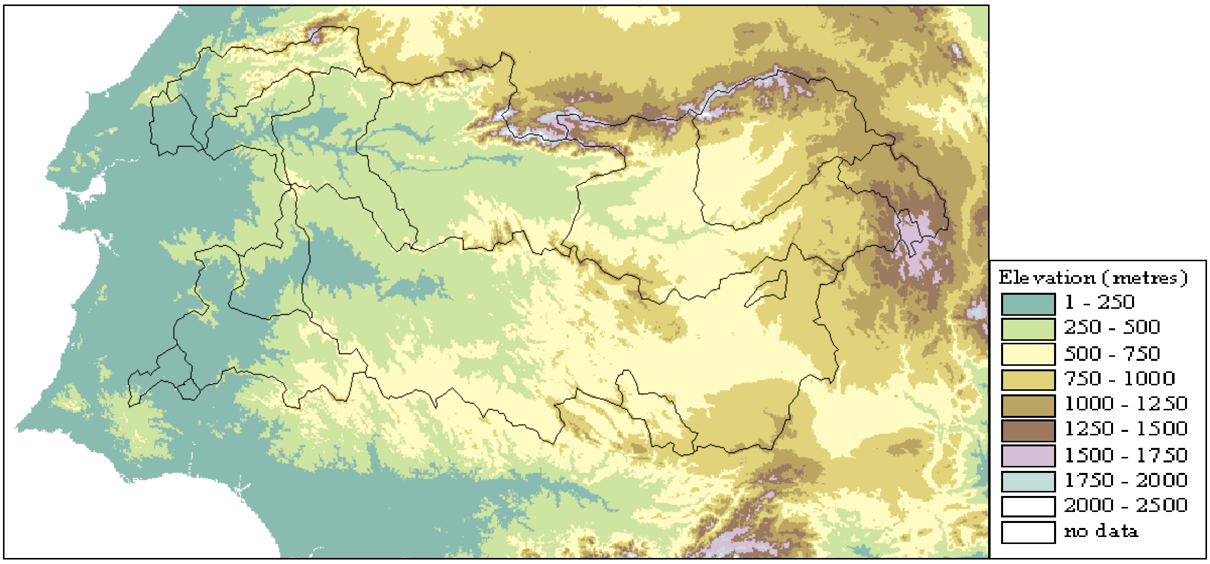
alleviate the effects of drought on river discharge but there is significant over-exploitation of groundwater resources in Spain (EEA, 1996, 2003). There is a considerable increase in water stress from north to south in both countries, and Portugal can be divided into two hydro-climatic zones, with the Tejo river acting as a natural border. The study area lies in the southern part (Figs. 1 and 2) where reservoirs are indispensable to ensure water requirements are met.

The Natural Mean Flow (NMF)* is equivalent to an effective rainfall of approximately 225 mm yr^{-1} in Spain and more than 400 mm yr^{-1} in Portugal (EEA, 1996); the European average is approximately 300 mm yr^{-1} (Table 2).

The Guadiana basin (71 573 km^2, 16% of which is in southern Portugal) has an average total runoff of only 90 mm yr^{-1}. It is the southernmost shared river and its lower reaches and estuary border both Spain and Portugal. The headwaters of the Guadiana are one of the driest areas of Europe, with an annual average rainfall of only 415 mm (Fig. 3). Precipitation is strongly seasonal, with June to August generally the driest time of year when PET (>800 mm yr^{-1}).

An increase of water storage in the Guadiana catchment, to satisfy the large water consumption from agricultural projects and public water supply, has modified the natural regime of the river significantly, notwithstanding climate change. The annual Spanish storage capacity in the area increased from almost zero in 1954 to 4000 m^3 × 10^6 in 1963 (Brandão and Rodrigues, 2000) and to 12 000 m^3 ×

* The total gross surface water resources (NMF) of Portugal and Spain have been evaluated by the Portuguese National Water Institute (INAG, 1995) at 3000 m^3 and 6400 m^3 per capita/year, respectively. 2000m^3 is indicative of water resource stress.



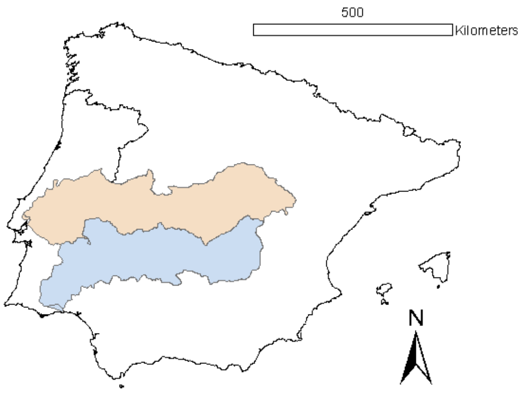


Fig. 1. *Location and topography of the study area*

10^6 in 1991. In the upper Guadiana, input has been reduced (445 $m^3 \times 10^6\ yr^{-1}$, reflecting drier than average conditions between 1974 and 1994),while the output increased (668 $m^3 \times 10^6\ yr^{-1}$).

Analysis of changes in flow during the period of observation is complicated by the increased storage associated with the construction of major dams in the 1950s and 1960s. The influence of human control on stream flow is clearly visible after 1956/57 in the hydrograph series.

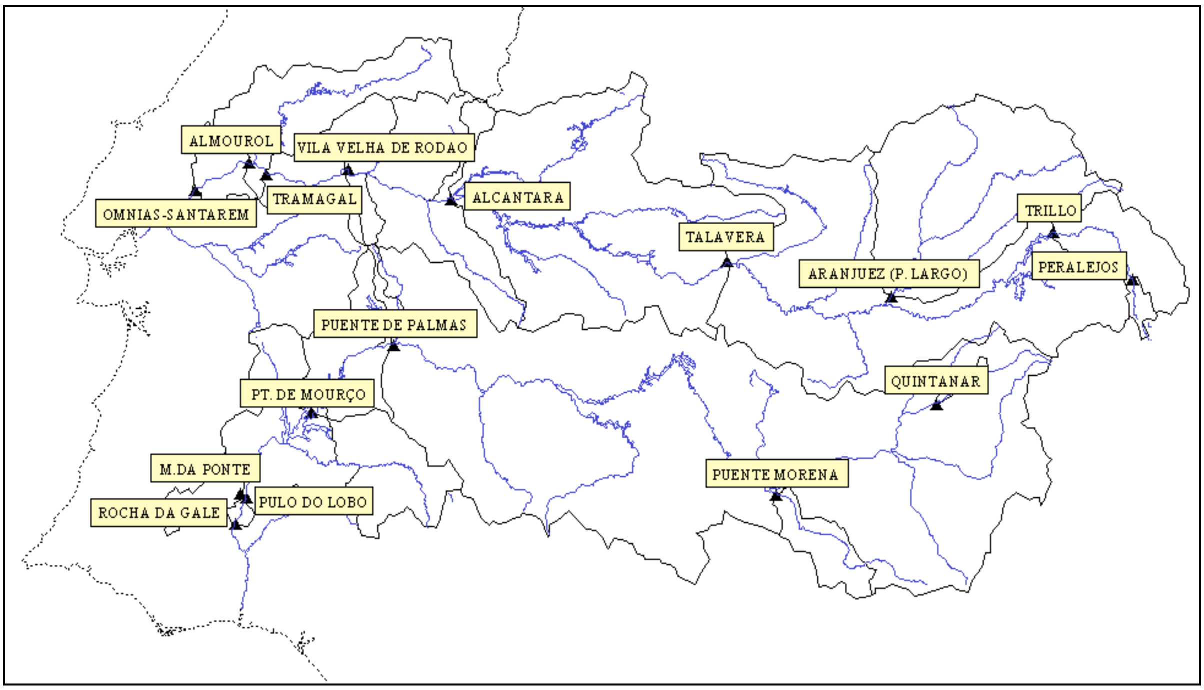


Fig. 2. *Gauging stations with available data in the Guadiana (southern) and Tejo (northern) basins*

Table 2. Comparison of minimum guaranteed flow volumes ($10^6 m^3$) with the current yearly flow volumes in dry years (Q_{dry}) (from Maia, 2000)

Water use	Q_{mig} [1]	Q_{dry} [2]	Q_{mig}/Q_{dry}	Q_{res} [3]	Q_{mig}/Q_{res}
Tejo	2700	3730	72%	2450	110%
Guadiana	300 to 600	600	50 to 100%	799	38% to 75%

[1] Q_{mig} is the minimum guaranteed flow volume
[2] Q_{dry} is the current yearly flow volumes in dry years
[3] Q_{res} is the minimum reserved flows – 20% of the Spanish river basin natural mean flow

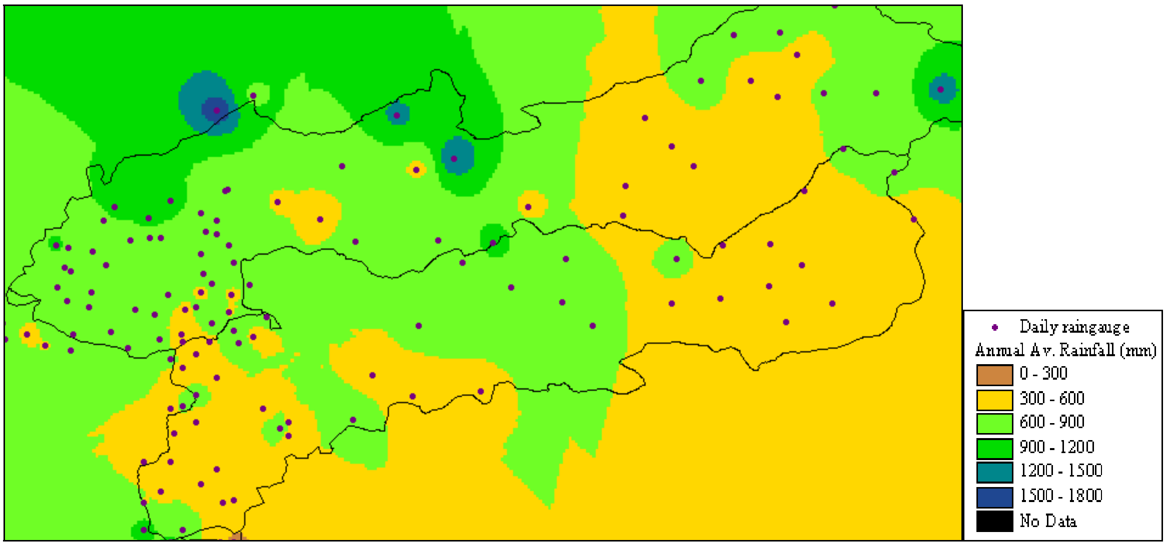


Fig. 3. *Long term mean rainfall (1961–1990) generated from surface Interpolation by Inverse Distance Weighting: locations of daily rainfall gauges are also shown.*

Trigo *et al.* (2004) Comparison of the flow regime of the Guadiana river basin for 1946–56, 1963–88 and 1990–98 revealed a strong decrease during the 1990–98 period which could not be explained solely by a strong decrease in precipitation and/or increase in upstream water abstraction. After 1995, a run of wetter-than-average years prompted a partial recovery of the regional water table (Bromley *et al.*, 2001). However, 2004–2005 has seen a continuation of a decline in resource, with the most severe drought on record in parts of Portugal, as described previously. For this reason calibration of the hydrological model over earlier periods will be preferred here.

INTERNATIONAL WATER AGREEMENTS

Brandão and Rodrigues (2000) simulate time series of runoff in the Portuguese part of the Guadiana catchment accounting for river regime modifications, excluding climate change, for six hydrological scenarios. Each scenario comprises a different flow series as input at the Portuguese border and monthly natural regime flows were obtained using a water balance model, calibrated for unregulated river flows using data for the period 1941 to 1990. Projections were made under natural (I) and actual (II) flow regimes, and for scenarios without (III and IV) and with (V and VI) restrictions imposed in the new water Convention, namely:

- The annual flow at the Portuguese border cannot be less than 600 $m^3 \times 10^6$
- The annual flow in three consecutive years cannot be less than 2400 $m^3 \times 10^6$

From the analysis they conclude that storage generally satisfies demand and a few reservoirs are able to meet further increases. However, after the 24th year of simulation, the number of months where the minimum ecological flow to the Guadiana estuary is not met increases considerably. The reliability of the ecological flow occurrence downstream of the Alqueva dam decreases from 100% (scenarios I and V) to 98% (scenario IV), and in the Guadiana estuary from

Table 3. Monthly mean flow (10^6 m^3) characteristics in the Guadiana estuary for six scenario runs (from Brandão and Rodrigues, 2000)

Scenario		*Oct*	*Nov*	*Dec*	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sep*
I	Natural flow regime	87	213	635	1032	1240	1044	357	189	28	8	7	8
II	Actual flow regime	55	101	341	617	808	659	230	44	11	8	7	8
III	2002 without convention	55	100	336	595	754	605	212	39	11	8	7	8
IV	2012 without convention	55	97	328	558	681	547	186	35	11	8	7	8
V	2002 with convention	55	100	336	610	812	649	212	39	11	8	7	8
VI	2012 with convention	55	97	328	577	713	585	186	35	11	8	7	8

91% (scenario I) to 89% (scenarios II, III, IV and VI).

The interdependency of Portuguese and Spanish water resources suggests that conservation policies and water resources planning should be co-ordinated and made compatible. Recommendations for regional water management have been proposed (Bromley *et al.*, 2001). The new Convention on Cooperation for Portuguese-Spanish River Basins Protection and Sustainable Uses, signed by the two governments but still to be ratified, demonstrates the commitment to shared water resources development and management. Maia (2000) summarises the scope, co-operation procedures, measures, exceptional situations and conflict resolution included in the Convention.

The current and foreseen pressures on water resources, including climate change, and respect of flow regime statements defined in the 1964 and 1968 conventions, must be addressed. Although minimum flows have been defined (in terms of total annual flow), no explicit allowance for exceptional years is made.

Hydrological Modelling

PREVIOUS STUDIES

Few studies have been undertaken regarding climate change impacts in the Guadiana and Tejo river basins. Previous work was on groundwater in the Upper Guadiana basin and on over-exploitation of its aquifer (Bromley, 2001; Acreman, 2001; Conan, 2003). A study by Brandão and Rodrigues (2000) applied a rainfall-runoff model for various scenarios but did not consider future climates. Trigo *et al.* (2004) considered the influence of the NAO on precipitation, river flow and water resources in the Iberian Peninsula but without the use of a hydrological model.

MODEL DESCRIPTION

UP2 is a conceptual rainfall-runoff and routing model, essentially a simplification of the UP model (Ewen *et al.*, 1999; Kilsby *et al.*, 1999) with the runoff algorithm based on the Xinanjiang probability-distributed soil-moisture scheme (Zhao, 1992) which is also implemented in the Arno (Todini, 1999) and VIC-2L (Liang *et al.*, 1996) models. 'Quick' and 'slow' runoff processes are modelled, where the quick process is represented by the Arno scheme for surface runoff, and the slow process is represented by drainage from the surface soil layers into sub-surface transfer to the channels. The distributed daily runoff, from the surface water compartments, is routed to the gauging station outlets by a transfer function scheme via a number of intermediate points on the network to the basin outlets.

The river basin is divided into elements (Fig. 4) which are the basic components of the simulation model. Each element (10 km × 10 km in this study) contains three

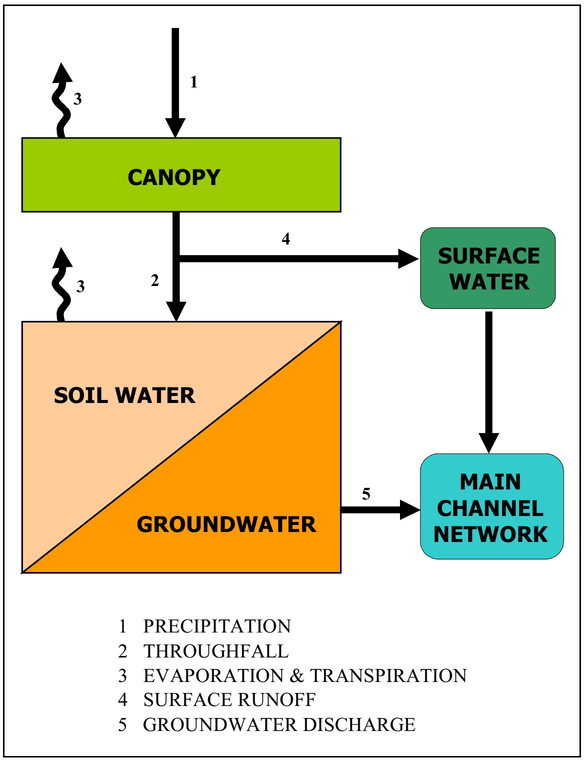


Fig. 4. *A schematic diagram of an UP2 element*

conceptual water storage compartments: vegetative canopy, surface water and soilwater (snowpack and deep groundwater are not considered in this application). To minimise the total number of parameter sets, each of the elements is categorised as being one of only a few types. The rate of water transfer between, into and out of compartments is controlled by the parameters. The key simulation variables are the volumes of water in the water compartments; simple budgeting is undertaken to maintain mass balance. Spatial inputs and responses are averaged over each element.

Variation in land cover is represented explicitly in UP2. Land cover, taken from the 1-km IGBP data set is reclassified to four types and the percentage of each type within individual elements extracted. Interception and evaporation parameters are then assigned according to the proportion of land cover within each element. Total evaporation is calculated as the sum of canopy evaporation, transpiration and bare soil evaporation, weighted by the fraction of surface area for each surface cover class Water storages, represented by 'state variables', are updated daily via mass balance equations.

MODEL PARAMETERISATION

Parameters have not been evaluated by direct measurement, so effective values are determined via calibration, within physically plausible bounds where appropriate. The parameters used for calibration are described below and summarised in Table 4.

The soil water storage probability distribution is controlled by two parameters: W_m defines the maximum water storage, varying between 200 and 450 mm here, whilst *b* controls the shape of the distribution. Generally, larger values of *b* generate higher runoff ratios. Drainage is a non-linear function of soil water above a threshold, W_d, controlled by parameter *c*. Drainage is linear below this threshold (Eqns. 1 and 2).

Actual evapotranspiration is calculated as a linear function of PET, limited by soil moisture at field capacity (AE = PET) and at wilting point (AE = 0). Effective rainfall is calculated using a simple canopy interception model.

The surface water and groundwater generated from each of the UP elements is routed through the channel network with an analytical solution to the St. Venant equations using channel transfer functions derived from channel network information, including distances, widths and roughness (Kilsby *et al.*, 1999). The approach is similar to the unit hydrograph theory, whereby discharge at the catchment outlet is estimated by linear superposition of unit hydrographs.

MODEL SET-UP

Initially, nine sub-catchments (four for the Guadiana basin and five for the Tejo) were delineated for separate parameterisation based on stream gauge locations (Fig. 2). These were subsequently simplified to two in each basin (Fig. 5). So for the Tejo, for example, the Talavera, Trillo and Aranjuez catchments were aggregated. These sub-catchments are simulated independently and the simulated discharge is routed downstream using a time-lag component (flow velocity is assumed to be spatially and temporally uniform and taken as 1 m s^{-1}). This simplification is acceptable as the daily simulation results are then aggregated to monthly flows for analysis. Particular attention has been paid to the lowest stream gauges on each basin, the catchment outlets at Almourol (Tejo) and Pulo do Lobo (Guadiana).

Rainfall records were obtained via the Portuguese Instituto de Meteorologia (IM) and the Fundación para la Investigación del Clima (FIC) of Spain. Rainfall data post-1995 are processed and archived by the Portuguese National Water Institute INAG. Daily observations were obtained for 50 stations. For the same period, INM station records number 67 and 18 respectively for the Tejo and Guadiana. The availability and quality of data were variable and not all records were used. Finally, 87 stations with less than 5% missing data were selected on the basis of record length and elevation (to ensure a representative coverage across the basin) (Fig. 6).

UP2 takes inputs of daily rainfall data and monthly PET. The rainfall inputs are processed using the rain gauge

Table 4. Primary model parameters associated with soil moisture storage and infiltration

Parameter	*Description*
D_{min}	Minimum drainage quantity, expressed as a percentage of D_{max}
D_{max}	Maximum drainage quantity
b	The shape parameter of the runoff distribution function
W_d	Moisture content threshold value
W_m	The maximum water storage capacity in the basin

Fig. 5. *Sub-basin set up for UP model*

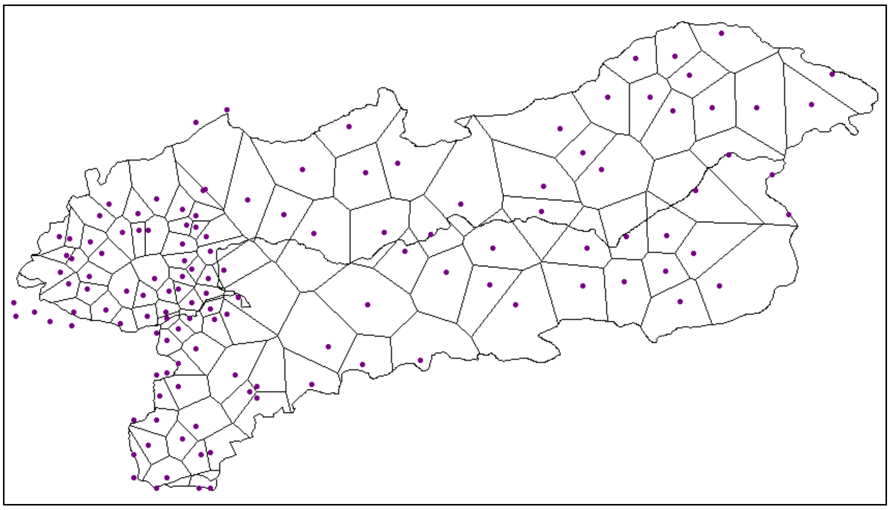


Fig. 6. *Thiessen polygon coverage of the rain gauges with available data*

locations and the Thiessen polygon method to find the nearest gauge. A 'spin-up period' of one year is used to start the model: the outputs for this period are discarded.

Generally, the model outputs show that surface runoff is acceptably well-simulated, particularly for the peak flows. The model does not account for groundwater interactions in the upper Guadiana, and may therefore not represent baseflow well, e.g. augmentation of low summer flows. As will be discussed later, for flows in the lower Guadiana and Tejo these errors are small compared to the overall flows and other uncertainties introduced by abstraction and regulation.

The seasonality of the mean monthly discharge at the Guadiana outlet is more accentuated for the 1960–1980 period than for 1981–1994 (Conan, 2003). After 1982, the date of completion of the El Vicario reservoir, the streamflow is reduced; this may cause model over-estimation of the streamflow in the upper Guadiana catchment.

MODEL CALIBRATION

A split-sample calibration and validation strategy was followed. The Guadiana and Tejo models were calibrated for the period 1970–1975 and the period 1975–1980 was used for validation. A local-scale approach was adopted. Upstream sub-catchments were calibrated first. Outlets located downstream of the main channel were initially avoided due to possible upstream influence. A simple time-lag function was used to transfer the discharge from the upstream outlet to the downstream outlet.

A Nash-Sutcliffe index of performance using monthly flows was used to assess model calibration. Some parameters were fixed at values derived from previous model applications: these include w_{fc}, w_{wilt}, and the drainage and vegetation parameters. An automated optimisation was then used to find the key parameters W_m and b. Manual calibration was carried out in the Puente de Palmas catchment. The calibrated UP model parameter sets for each land use and all catchments are given in Tables 5 and 6.

Table 5(a). Parameter values for each of the land covers

Parameter	*Woodland*	*Shrub land*	*Grassland*	*Crop land*
l	1.5	1.0	1.0	1.0
f	0.9	0.8	0.8	0.9
C_{max}	2	1.2	1.0	1.0

Table 5(b). Parameter values for each sub-catchment

Parameter	*Almourol*	*Talavera*	*Pulo Do Lobo*	*Puente de Palmas*
b	0.01	0.01	0.01	0.8
Wm	300	400	300	400
Dmin	0.01	0.01	0.01	0.01
Dmax	0.2	0.1	0.4	0.06
Wd	0.04	0.4	0.4	0.9
W_{wilt}/W_{max}		0.2		
W_{fc}/W_{max}		0.7		

Table 6. Changes in mean daily rainfall for future scenarios.

	Direct			*CP*		
	Control	*Future*	*Change (%)*	*Control*	*Future*	*Change (%)*
GUADIANA BASIN						
Oct	1.74	1.13	-35.1	1.83	1.67	-8.6
Nov	2.40	1.96	-18.5	2.42	2.31	-4.4
Dec	2.29	1.86	-18.7	2.33	2.22	-4.5
Jan	2.14	2.15	0.2	2.33	1.66	-28.7
Feb	2.42	1.38	-43.0	2.16	1.60	-25.8
Mar	1.57	1.13	-27.6	1.70	1.31	-23.0
Apr	1.97	1.08	-45.4	2.00	1.57	-21.5
May	1.33	0.73	-45.0	1.41	1.13	-19.8
Jun	1.06	0.47	-55.0	1.05	1.02	-2.6
Jul	0.25	0.11	-53.9	0.27	0.24	-11.0
Aug	0.26	0.08	-67.2	0.26	0.28	5.4
Sep	0.92	0.65	-29.2	0.91	0.82	-9.1
Annual	1.53	1.06	-30.5	1.55	1.32	-15.1
TEJO BASIN						
Oct	2.12	1.31	-38.4	2.23	2.02	-9.7
Nov	3.00	2.72	-9.4	3.02	2.88	-4.8
Dec	2.73	2.46	-9.9	2.79	2.72	-2.5
Jan	2.72	3.06	12.3	2.94	2.08	-29.0
Feb	2.95	1.90	-35.5	2.64	1.99	-24.9
Mar	1.71	1.30	-24.0	1.83	1.53	-16.3
Apr	2.23	1.33	-40.2	2.24	1.88	-16.4
May	1.71	1.00	-41.3	1.82	1.60	-12.3
Jun	1.25	0.61	-51.6	1.24	1.37	10.2
Jul	0.40	0.19	-52.8	0.42	0.47	11.3
Aug	0.35	0.13	-64.1	0.37	0.43	17.0
Sep	1.19	0.94	-20.7	1.17	1.15	-1.3
Annual	1.86	1.41	-24.3	1.89	1.68	-11.5

Reasonable values of R^2 (both 0.70) are obtained for calibration at Pulo do Lobo and Almourol. There is reasonable reproduction of the hydrographs on a monthly basis (Figs. 7 and 8). Note that these periods are before major regulation and abstractions were implemented and the simulated flows (particularly in winter) are reasonably close to those observed.

MODEL VALIDATION

The catchment discharges were validated using data from 1975 to 1980. The results (Fig. 9) are a better fit than the calibration simulations, giving confidence in the model performance. Nash-Sutcliffe efficiencies of 0.75 at Almourol and 0.93 at Pulo do Lobo were obtained. The validation period is wetter, with higher flows than the calibration period, so it is to be expected that the model will perform better then because the Nash-Sutcliffe efficiency in model fitting gives greater weight to high flows.

The model was then tested against the 1961–1990 period for the Guadiana catchment and 1973–1990 for the Tejo catchment. Both of these long simulations gave acceptable results (Figs. 10 and 11). However, later in the period, and especially in the Guadiana, a pronounced over-estimation by the model for low flow periods is caused by an absence of the representation of abstraction and water management measures in the model.

Climate change study

The validated hydrological model was then used for simulation of future climates using two methods for generating future climate scenarios. Firstly, outputs from a Regional Climate Model (RCM) were used directly, with bias correction (denoted Direct). Secondly, rainfall data were generated using a circulation-pattern based method for 42 stations over the Tejo and Guadiana river basins (denoted CP).

RCM PRECIPITATION SCENARIOS

Future rainfall series were generated using a methodology previously applied in a NW England water resource system study (Fowler *et al.*, 2007) and described more fully in Fowler and Kilsby (2006). The procedure takes daily rainfall outputs from the HadRM3H future scenario and uses them directly as inputs to the hydrological model after applying a monthly bias correction based on the difference between the observed and HadRM3H control rainfall. The data are derived from the HadRM3H grid of approximately 50 km resolution, shown in Fig. 12.

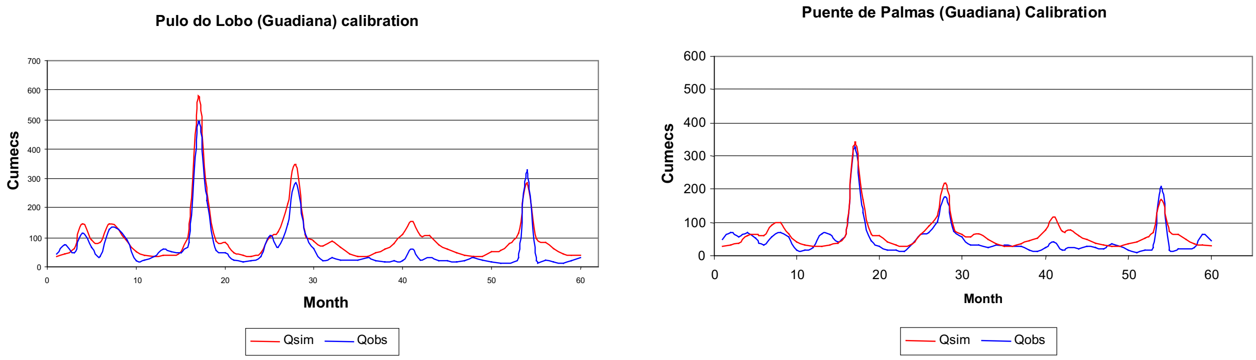


Fig. 7. *Hydrographs for model calibration for the Guadiana catchment*

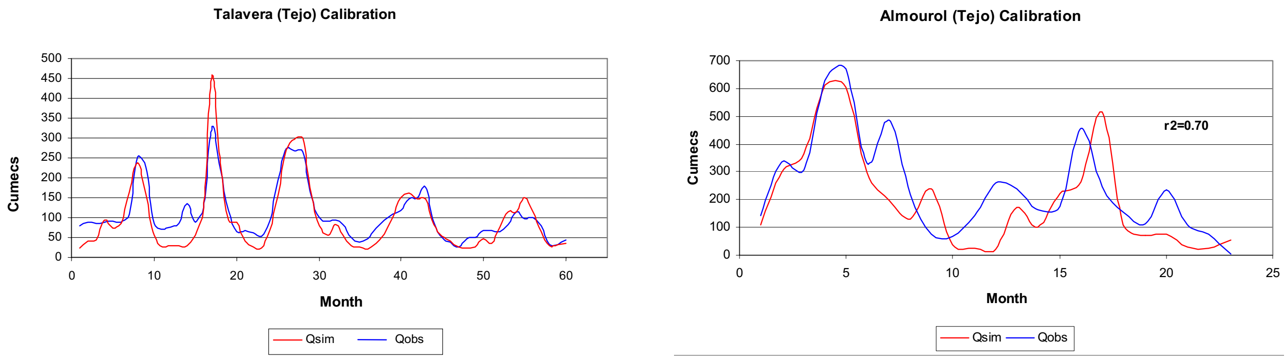


Fig. 8. *Hydrographs for model calibration for the Tejo catchment*

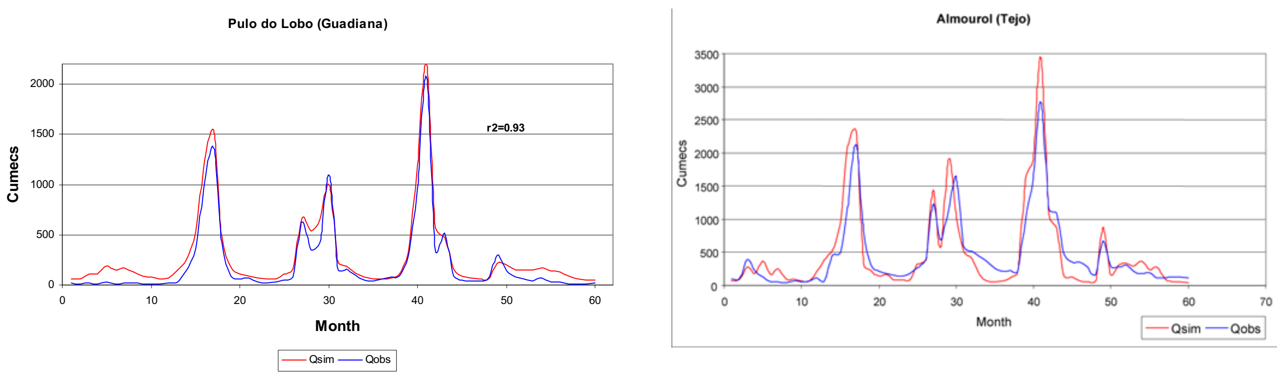


Fig. 9. *Validation results for Guadiana and Tejo basins*

The mean of the three control series was used for bias correction. Long-term means of the series for each basin are shown for comparison with the observed in Fig. 13. Both control and observed series have been area-averaged for the basins using the Thiessen-polygon method for each gauge record.

The future series for 2070–2100 were used in this assessment, for the more severe SRES A2 scenario. The ensemble of three simulations for the A2 scenario is used, providing 90 years of data, used here as three thirty-year series. This has the advantage of providing simulations of the same length as the observed record as well as giving an estimate of natural variability. Figure 14 shows the changes in basin-average rainfall for the Guadiana and Tejo for the period 2070–2100.

PET data for the future case was modelled using the

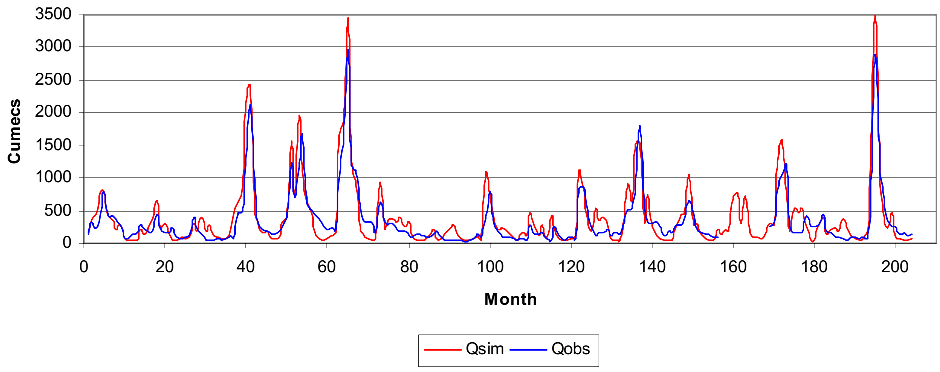


Fig. 10. *Tejo: simulation results at Almourol station for the period 1973–90*

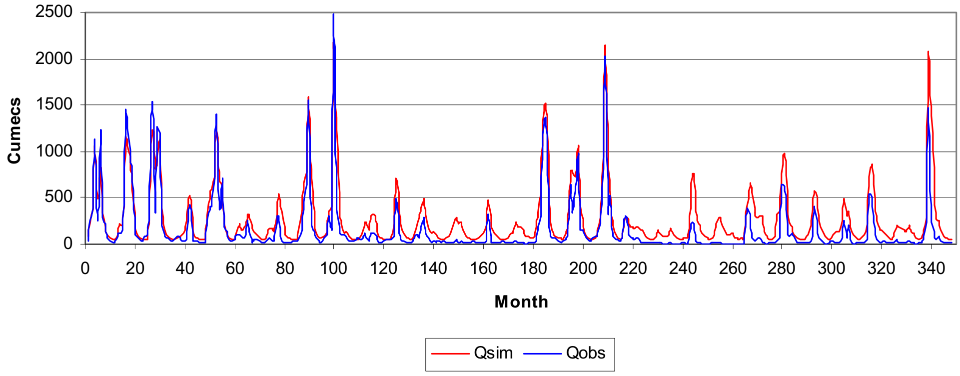


Fig. 11. *Guadiana: simulation results at Pulo Do Lobo station for the period 1961–90*

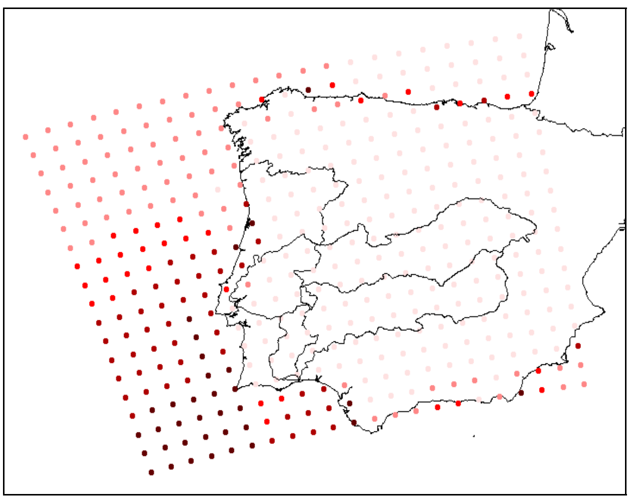


Fig. 12. *The HadRM3H grid together with political boundaries and the Tejo and Guadiana catchment boundaries*

observed series multiplied by a factor, based on estimates of PET future change in the region using the Penman equation (see Ekstrom *et al*., 2007, for more details). This increase amounts to some 40% or more annually across the region, although large increases in PET in summer will have little effect on actual evaporation as available moisture is low at that time of year.

CIRCULATION PATTERN DERIVED SCENARIOS

The second set of scenarios was produced using a multi-site stochastic weather model conditioned on large-scale daily circulation patterns. This is fully described in Xu *et al*. (2007). Three 100-member ensembles of 30-year daily rainfall series were supplied, conditioned on circulation patterns taken from (a) the observed historic period, 1961–1990, (b) the HadRM3H control, and (c) the HadRM3H future A2 scenario (as for the Direct scenarios described above). The long-term area-weighted basin averages of the historic and control series are shown in Fig. 13 for comparison with the observed. The historic series reproduce the observed means well, whilst the control series underestimates rainfall somewhat in the winter period.

Figure 14 shows the changes in basin-average rainfall for the Guadiana and Tejo for the period 2070–2100 alongside the equivalent for the direct scenarios. The means for the ensembles of each are also given in Table 6, where it can be seen that the CP-based scenarios exhibit a much smaller

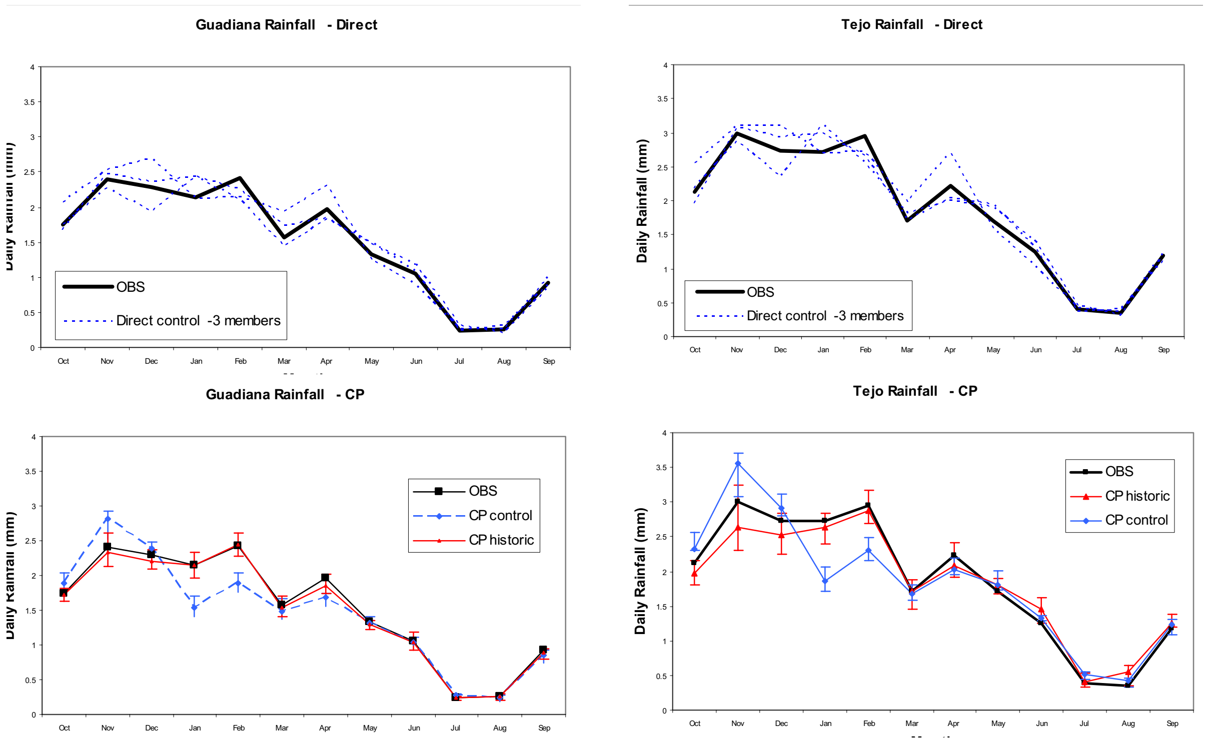


Fig. 13. *Long-term mean area-weighted daily rainfall for the control period (1961-1990) for the Guadiana (left) and Tejo (right) basins. The top row is for the Circulation Pattern (CP) based rainfall, showing the spread across ensemble members: error bars show 10th and 90th percentiles. The bottom row is for the RCM (Direct) rainfall, and shows the variation across the 3 ensemble members.*

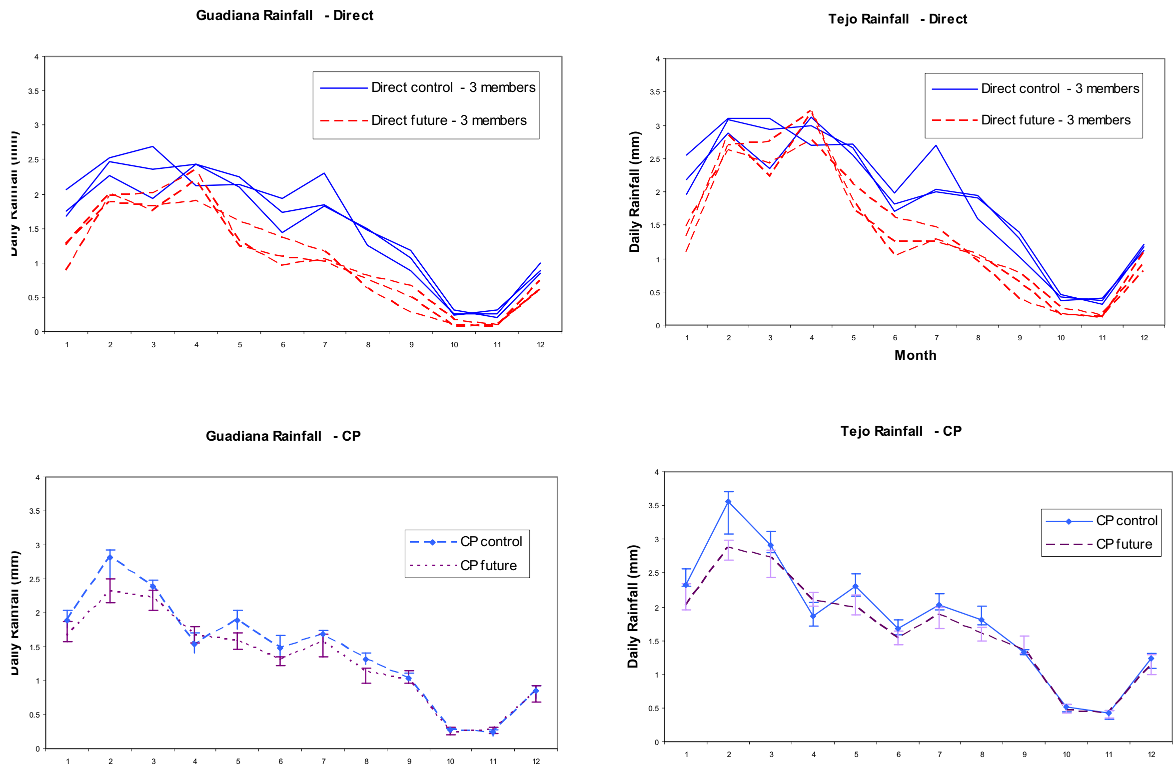


Fig. 14. *Long-term mean area-weighted daily rainfall for the future period (2070–2080) for the Guadiana (left) and Tejo (right) basins. The top row is for the Circulation Pattern (CP) based rainfall, showing the spread across ensemble members: error bars show 10th and 90th percentiles. The bottom row is for the RCM (Direct) rainfall, and shows the variation across the 3 ensemble members.*

reduction in rainfall for the future period (around –13% annual mean) than the direct scenarios (around –27% annual mean). Smaller changes in rainfall may be expected from circulation-based models, particularly if there are only relatively small changes in future circulation patterns derived from climate models. This difference could also be due to the Direct method incurring greater 'within weather-type' changes in rainfall, e.g. from increased convective forcing. Overall, this is indicative that generally smaller changes in future rainfall may be obtained using circulation-based downscaling methods.

Results and discussion

Control and future climate change impact simulations were performed for the Tejo and Guadiana basins using the rainfall-runoff model with the rainfall and PET series described above.

Control simulations (representative of the period 1961–1990) were performed using three ensembles of inputs: (1) Direct (RCM) rainfall series and CP-based rainfall series for two cases, (2) historic (rainfall model driven by observed CPs) and (3) control. Mean monthly discharges are shown in Figs. 15 (Tejo) and 16 (Guadiana).

Future simulations (representative of the period 2070–2100 for the SRES A2 emissions scenario) used two ensembles of inputs: (1) Direct (RCM) rainfall series and (2) CP-based rainfall series. Mean monthly discharges are shown in Figs. 15 (Tejo) and 16 (Guadiana).

The control simulations show reasonable agreement with observations, but with some significant differences. Although the CP historic simulations are in good agreement with observations for the Tejo basin, they are less good for the Guadiana, with significant over-estimation, particularly in spring and summer. This is consistent with the validation results and may be attributed to the major abstractions and management in the basin in later years, most prominent in spring and summer. The CP control simulations agree less well, due primarily to the less accurate reproduction of mean rainfall (Figs. 13, 14). For the Direct case, the control simulations again over-estimate flows throughout the entire year (Guadiana) and in spring and summer (Tejo).

The future impacts (Figs. 15 and 16, and Table 7) show significant reductions in flow throughout the year in contrast to previous studies which showed some compensating increases in winter flows due to higher rainfall (Corte-Real *et al*., 1998, 1999; Trigo and Palutikof, 2001). Reductions are much more pronounced for the Direct cases (annual reductions of 26% and 49% for Guadiana and Tejo respectively) than for the CP-based rainfall (21% and 20%); arising directly from the differences in rainfall scenarios. Reductions are much greater for the Tejo basin (49%) than the Guadiana (26%) for the Direct rainfall scenarios, whilst reductions are similar in both basins for the CP scenarios.

Conclusions

This impact assessment clearly projects a major reduction in future flows, caused by both the increase in PET and the year-round decrease in rainfall amounts. These reductions pose major threats to water supply in Portugal from the Tejo river (a key resource) and the Guadiana river (supplying the Alqueva reservoir and irrigation water for much of the Alentejo region and the south of Portugal).

Previous studies (based on HadRM2 and GCM outputs) have suggested that increases in winter rainfall may compensate for decreased summer rainfall: the results presented here however suggest year-round decreases in rainfall and stream flow. This has serious implications for the viability of the existing bi-partite water agreements between Spain and Portugal, which have already been breached recently. A key element of this study has been incorporation of a range of future rainfall scenarios. Whilst these have been based on a single GCM change scenario (HadCM3 SRES A2, 2080s), a wide range of conditions has been generated using two means: firstly, by downscaling using two different methods and, secondly, by using ensembles of series from each method. The two downscaling methods are (a) directly using the dynamically downscaled HadRM3 rainfall outputs, and (b) using a stochastic rainfall model conditioned on circulation patterns. Three ensemble members were available in the case of the Direct RCM series and 100 in the case of the CP based method.

Larger reductions in rainfall were obtained for the Direct scenarios than for the CP-based scenarios. This is not surprising, since the CP-based method works by changing the relative frequency of existing weather types or rainfall systems, whereas the direct method allows changes to the rainfall generation of a given weather type, thus allowing further reduction or enhancement. Intra-ensemble differences were also smaller for the CP based scenarios.

Strategies for the assessment of future resources would benefit from further improvement of the hydrological modelling. A major difficulty in the modelling methodology is posed by the large degree of regulation and abstraction in the river systems. As a result, there is a large discrepancy between the observed flows and the simulated flows which correspond to natural conditions. This is most apparent for the latter years in the observed period (e.g. after 1980) when major reservoir storage and river abstractions were implemented. One strategy for correction would be to compare simulated (natural) and observed (regulated) flows

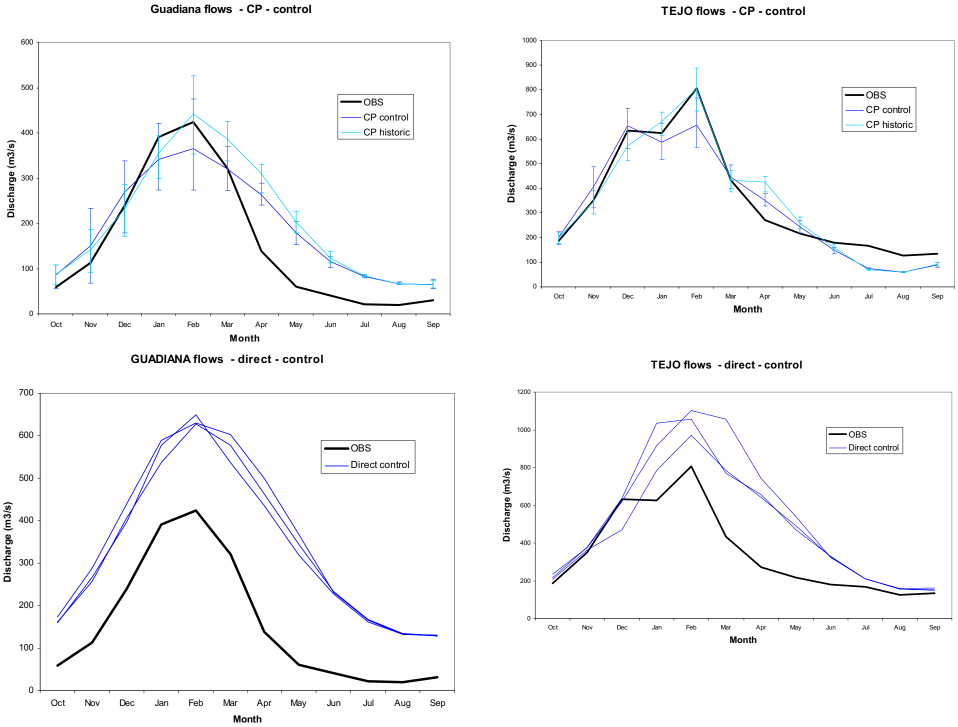


Fig. 15. *Long-term mean streamflow for the control period (1961–1990) for the Guadiana (left) and Tejo (right) basins. Top row is for the Circulation Pattern (CP) based rainfall, showing the spread across ensemble members: error bars show 10th and 90th percentiles. The bottom row is for the RCM (Direct) rainfall, and shows the variation across the 3 ensemble members.*

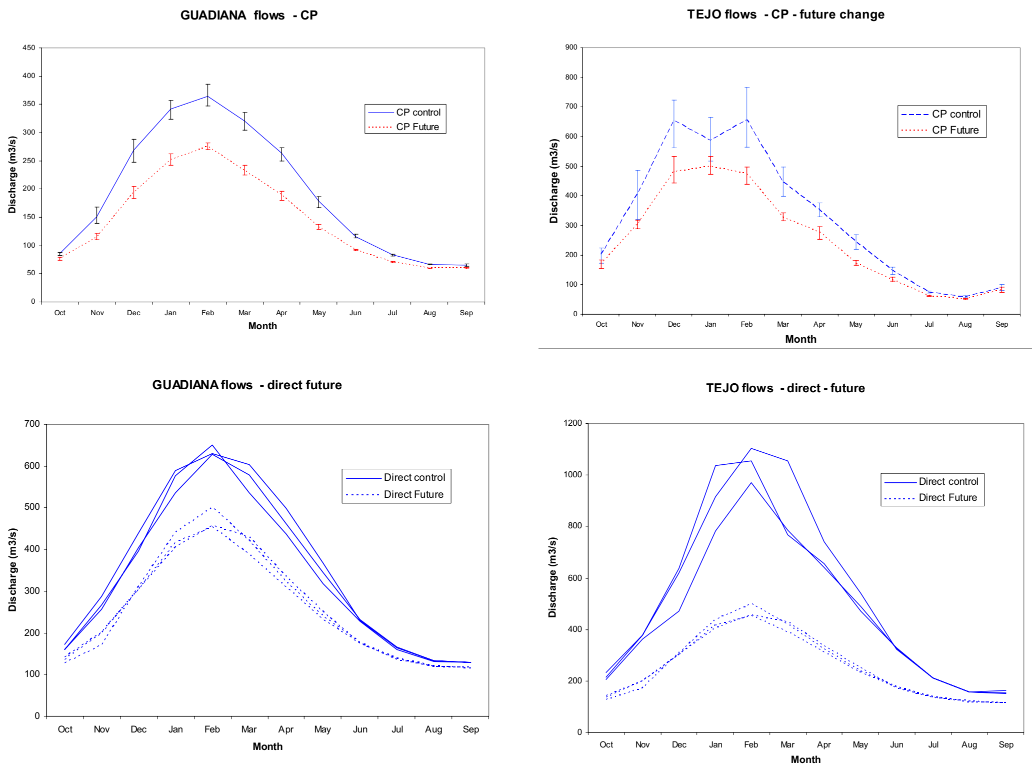


Fig. 16. *Long-term mean streamflow for the future period (2080–2100) for the Guadiana (left) and Tejo (right) basins. Top row is for the Circulation Pattern (CP) based rainfall, showing the spread across ensemble members: error bars show 10th and 90th percentiles. The bottom row is for the RCM (Direct) rainfall and shows the variation across the 3 ensemble members.*

Table 7. Changes in mean monthly streamflow for future scenarios. Change figures are given as percentage changes in the ensemble mean relative to the control value. Max and min changes refer to the direct scenarios, whilst the 10% and 90% changes refer to the CP scenarios.

		Direct					*CP*				
	Obs	*Control*	*Future*	*Change*	*Max*	*min*	*Control*	*Future*	*Change*	*10%*	*90%*
GUADIANA											
Oct	59	165	134	-18	-14.3	-22.7	86	77	-10.2	-12.5	-6.9
Nov	112	271	190	-30	-25.9	-36.8	151	115	-23.8	-27.7	-20.7
Dec	240	414	306	-26	-25.3	-26.7	269	194	-28.1	-32.1	-24.4
Jan	391	567	420	-26	-22.7	-28.7	342	252	-26.2	-29.2	-23.4
Feb	424	636	470	-26	-21.4	-28.7	365	275	-24.6	-26.6	-23.2
Mar	321	572	413	-28	-25.1	-32.1	320	232	-27.5	-30.6	-25.2
Apr	139	466	323	-31	-28.1	-33.4	264	190	-28.0	-30.4	-24.2
May	61	343	240	-30	-27.2	-32.5	179	133	-25.8	-28.5	-23.2
Jun	41	230	175	-24	-23.1	-24.6	116	92	-20.6	-21.5	-19.1
Jul	21	164	137	-16	-15.1	-17.5	83	71	-15.1	-15.9	-13.8
Aug	19	132	120	-10	-9.0	-10.4	67	60	-10.3	-10.9	-9.5
Sep	30	129	115	-10	-10.0	-11.0	65	60	-7.6	-9.3	-5.7
Annual	155	341	254	-26	-22.8	-28.3	192	146	-21	-26.7	-21.6
Tejo											
Oct	187	219	134	-38	-35.4	-41.7	201	170	-15	-22.1	-7.7
Nov	350	373	190	-49	-46.2	-54.1	404	305	-24	-27.8	-20.4
Dec	634	576	306	-47	-46.3	-47.3	653	482	-26	-34.1	-20.2
Jan	624	912	420	-54	-51.9	-55.6	586	500	-15	-20.3	-9.9
Feb	807	1044	470	-55	-52.1	-56.6	656	476	-28	-30.8	-21.8
Mar	433	870	413	-53	-50.7	-55.3	446	328	-27	-29.8	-24.0
Apr	271	679	323	-52	-50.6	-54.3	352	278	-21	-26.1	-14.2
May	216	501	240	-52	-50.1	-53.8	244	172	-30	-34.2	-27.5
Jun	180	326	175	-46	-45.7	-46.8	149	117	-21	-26.3	-17.1
Jul	167	211	137	-35	-34.1	-36.0	75	62	-17	-19.6	-14.1
Aug	127	157	120	-24	-23.5	-24.6	59	52	-11	-15.3	-7.7
Sep	133	155	115	-26	-25.3	-26.1	89	82	-8	-17.4	2.4
Annual	344	502	254	-49	-47.6	-51.3	326	252	-20	-27.8	-17.7

for an affected period (say 1980 to 1990) and to derive corrections for a range of quantiles taken from flow duration curves (e.g. Q90, Q50, etc.). These corrections would then allow the estimation, on average, of real flows from simulated flows, assuming that the same management regime has been continued.

Further analysis for resource management could set thresholds for reliability and the failure of resources; suitable thresholds may be selected by consideration of scenarios corresponding to the condition of exploitation used in the Spanish National Water Plan. The threshold for failure in a sustainability analysis could, for example, be that the flow at the Portuguese border should not fall below the thresholds set in bi-lateral treaties (i.e. 600 hm^3 annual mean flow or three-year total of 2400 hm^3.)

A further shortcoming of the model is the lack of a groundwater component for adequate simulation of the upper Guadiana. This is not a crucial issue for the simulation of flows at the outlet of the basins, but does preclude analysis of flows internal to the basin. Future development of the simulation capability should address this issue as well as the more important one of abstraction and regulation, perhaps through the use of a rules-based routing scheme.

Although two different downscaling methods have been used here, giving a wide range of projected future impacts, a more informative analysis would use a wider range of future rainfall and PET scenarios, following the PDF methodology described by Hingray *et al.* (2007). This would then allow a range of climate model outputs to be included, rather than just the HadRM3 outputs used here, and allow the uncertainty in future projections to be more fully explored.

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